#54

SUCCESSFUL HEMODYNAMIC RESULTS WITH A NEW, U-SHAPED AUXILIARY VENTRICLE

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Our earlier experience with an implantable, synchronous, arterio-arterial pump has been previously reported(1). Since then, in an effort to develop a system to support the failing left heart in man, we have focused(2) on several factors: a pump occupying as little space as possible in the left chest and topographically situated to permit normal functioning of all organs; a pump close enough to the heart for maximum assistance to the left ventricle and augmentation of coronary flow, yet interfering minimally with normal physiology when turned off; a device that is safe for intermittent operation; use of appropriate materials to minimize thrombus formation.

MATERIALS AND METHODS

The auxiliary ventricle (AV) consists of a flexible plastic bulb in a firm case of the same contour. It is connected by cuffs of Dacron arterial graft* to the ascending and descending aorta, paralleling the aortic arch. Two multistrand, stainless-steel, Teflon-coated electrodes+ implanted in the myocardium of the left ventricle pick up the R wave of the ECG. The R wave triggers a solenoid valve that controls the application of air to drive the unit. Compressed air is introduced into the space between inner bulb and housing via a plastic tube with 1/8" inside diameter. The time delay for the air valve, set while left ventricular and central aortic pressures are observed on an oscilloscope, is rarely changed afterward. The device, which follows the heart rate within any reasonable range, contracts in series with the physiologic left ventricle. It was developed jointly by our laboratory and the Avco Corporation.

The first units were ellipsoidal but during the past year we changed to an asymmetrical U-shape. It can be placed closer to the aortic root, with minimum risk of kinking the Dacron cuffs, and occupies less space in the left chest (Figure 1). It hugs the mediastinum leaving ample room for good expansion of the lungs which is vital in the early postoperative period and during prolonged use. The proximal arm leaves the unit at a 60° angle toward the mediastinum and 15° away from the distal arm, which emerges straight from the unit. Blood flows in a smooth curve from the aortic root through the proximal cuff to the booster heart, a distance of only 2.5 cm., lending effective hemodynamic support.

When the pump is turned off, blood flows through it in a wide curve bypassing the aortic arch, causing minimum turbulence. An end-to-side distal anastomosis permits perfusion of the cranial and caudal areas.

When the pump is turned on, the flexible bulb fills during systole of the natural heart (Figure 2). As it fills, the air between bulb and housing is forced out. The left ventricle works less hard to pump its blood to the nearby auxiliary ventricle (against atmospheric pressure) than to pump it to remote vessels (against normal peripheral resistance). The ejected air was at first vented to the atmosphere but for the past six months we have applied slight negative pressure to the tube, making it still easier for the left ventricle to empty its blood into the device.

Since blood is transported from one high pressure area to another, no inside valves are required, with less risk of clotting or traumatizing the blood elements. Backflow of a small amount of blood into the unit from the descending aorta is inevitable but, according to tension-time index calculations, this compromise is acceptable.

Cardiac diastole begins immediately after the aortic valves have closed. During diastole the auxiliary ventricle contracts by compressed air, ejecting blood into the peripheral vessels and coronary arteries.

The ascending aorta is ligated with umbilical tape distal to the anastomosis, making the bypass obligatory and thus discouraging clotting, especially when the unit is not functioning by ensuring a high flow through the unit at all times. This ligation has little effect on pressure and flow in the carotid and subclavian arteries.

The relatively simple implantation procedure is carried out through a left chest thoracotomy at the 4th intercostal space. The aortic root and proximal descending aorta are exposed and partially clamped. The cuffs are anastomosed to the aorta with continuous 4-0 cardiovascular silk. Two

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*DeBakey Seamless Arterial Graft, 10 mm. and 12 mm. diam., C.R. Bard, Inc., Murray Hill, N.J.
+Flexon #0 Atraumatic Needles, American Cyanamid Co., Davis & Geck Division, Danbury, Conn.

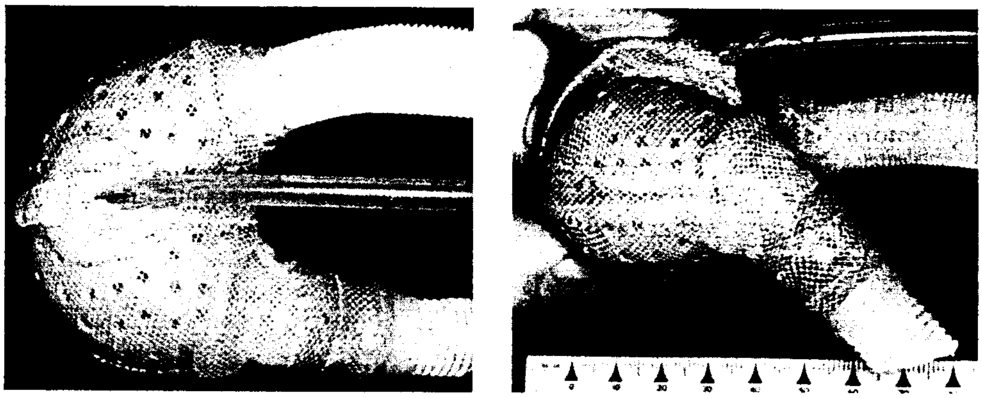

Figure 1. Two views of Silastic auxiliary ventricle show angle of inset arms and relative length of woven Dacron cuffs.

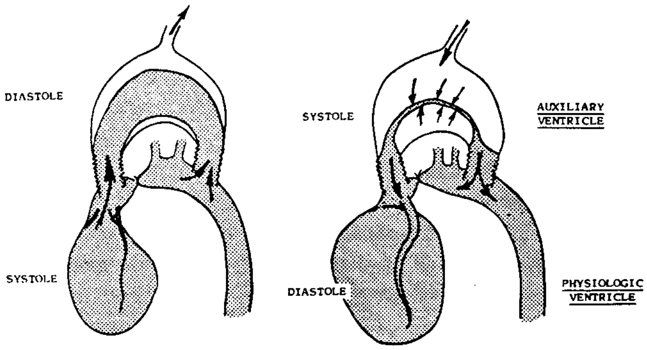

Figure 2. During diastole of auxiliary ventricle (AV), bulb fills with blood as air is removed by suction, lowering resistance of left ventricle to emptying and thus reducing its work. During AV systole, air contracts bulb which expels its blood into arterial tree, increasing diastolic pressure as well as peripheral and coronary flow.

Figure 3. X-ray of Dog #2065 with polyurethane unit implanted four months earlier: radiopaque dye injected into left ventricle outlines patent bulb and vessels.

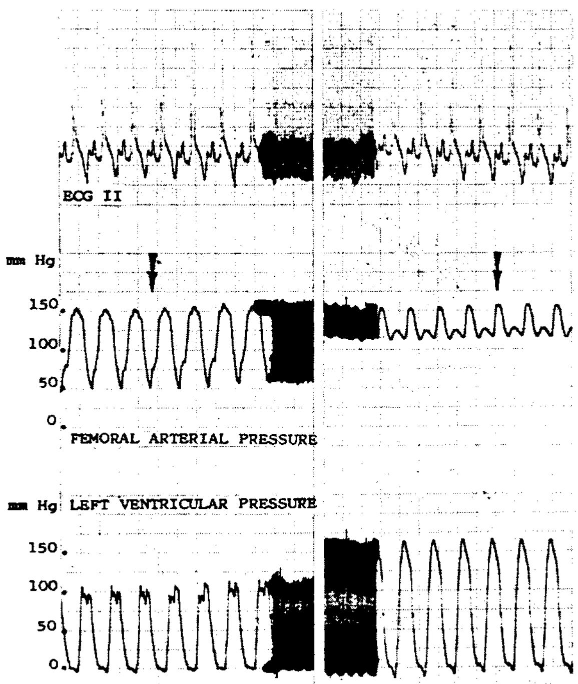

Figure 4. Reading from top: ECG (lead II), femoral arterial pressure and left ventricular pressure with auxiliary ventricle "on" (left) and "off" (right). Arrows indicate cardiac systole.

electrodes are placed in the myocardium of the left ventricle to pick up the ECG. No pump-oxygenator or heparinization is needed.

We have recently constructed a ring connector enabling us to place the obliquely cut proximal cuff very close to the aortic root, achieving minimum angulation. A metal ring is smoothly sealed to the proximal arm of the device. A short Dacron cuff, with a plastic extension fitting the ring, is independently anastomozed to the partially clamped ascending aorta. After the unit is properly positioned, the plastic extension is slipped over the ring and affixed with a single tie.

The section of the plastic air tube extending from the muscle through the subcutaneous tissue to the skin level--about 4.0 cm.--is wrapped with Dacron felt. Fibroblastic invasion of this porous material seals the tube firmly in place. The electrodes are brought out separately through the skin. We are still having difficulties in constructing a suitable, more sophisticated access plug.

The U-shaped units have been made in two materials.

Silastic 372 Units. A polyethylene[*] case for the inner bulb is made in a Silastic[+] mold. After the cast surface has been smoothed by scalpel and by heat, it is coated with a polyvinyl alcohol[#]. When completely dry, the cast is layered with Silastic 372[(3,4)] reinforced with 0.030" Dacron mesh[x]. Care is exercised to prevent irregularities at the juncture lines. The layered cast is autoclaved at 260° F. for 30 minutes, which melts out the polyethylene. The water-soluble alcohol is then rinsed out, leaving a flexible Silastic bulb. A coating of Silastic adhesive[z]-xylene solution makes a smooth inner surface.

The two plastic aluminum[&] shells are molded in forms of Silastic 382[v]. The construction process is shortened by warming the mold slightly and using accelerator supplied with the liquid aluminum. Holes are drilled in the hardened shells, and they are then dipped in the same Silastic-xylene solution. The outer surface is covered with the Dacron-reinforced Silastic. When the flexible bulb is placed between the two shells, the air tube is inserted and affixed with the Silastic adhesive, which is also used to seal the shells. The whole unit is given a last coat of Dacron-reinforced Silastic.

Polyurethane Units. Although we consider Silastic 372 the most satisfactory available material for the auxiliary ventricle--from the standpoint of tensile strength, long-term durability and minimum thrombus formation--we are continuously searching for other, possibly better materials. One effort in this direction, a modification of Gott's method[(5)], is applying a coating with a negative zeta potential to the bulb's inner surface. Since practically no chemical adheres firmly to a Silastic surface, we use polyurethane[o] dissolved in cyclohexanon and tetrahydrofuran and add colloidal graphite[%] to it. The bulb cast, prepared as for the Silastic unit, is coated twice with this mixture, then twice with pure polyurethane which has a higher tensile strength. The dry bulb is cut open for removal of the cast and carefully reconstituted with the polyurethane-graphite mixture. The metal ring connector and the Dacron cuffs are also sealed with it. The stiff housing consists of two plastic aluminum shells covered with a polyester mesh[s]. After holes are drilled, they are dipped in pure polyurethane. The bulb's inner surface is finally coated with a colloidal graphite-xylene solution. The polyurethane bulb is oven-dried for 24 hours at 56°C., then soaked overnight in 2.0% benzalkonium chloride solution, and for one hour in a heparin-saline solution.

RESULTS

Patency Studies. We have implanted U-shaped units, six of Silastic and seven of treated polyurethane, in the optimal bypass position in 13 dogs for long-term patency testing. These nonfunctioning bulbs offer a more severe test of clotting than functioning units which produce more movement and thus prevent blood stagnation. There was less trauma to the blood elements with the nonfunctioning bulbs;

[*]Epolene, Eastman Chemical Products, Inc., Kingsport, Tenn.
[+]Silastic RTV 589, Dow Corning Corp., Midland, Mich.
[#]Elvanol, Grade 50-42 Polyvinyl Alcohol, E.I. DuPont de Nemours & Co., Electrochemicals Dept., Wilmington, Del.
[x]Silastic 372 Medical Grade Sheeting Reinforced with Dacron, Dow Corning Corp.
[z]Medical Adhesive 891, Silicone Type A, Down Corning Corp.
[&]Devcon F-2 Aluminum Liquid, Devcon Corp., Danvers, Mass.
[v]Silastic RTV 382 Medical Grade Elastomer, Dow Corning Corp.
[o]Estane VC 5700 x 101, B.F. Goodrich Co., Research Center, Brecksville, Ohio.
[%]Dag Solution 35, Acheson Colloids Co., Port Huron, Mich.
[s]Mersilene RM 54, Polyester Fiber Mesh, Ethicon Inc., Somerville, N.J.

no animals became anemic or showed other major changes in blood profile.

One of the six dogs with a Silastic bulb died on the 16th day of multiple emboli found at points where the Silastic sheeting was joined. We subsequently coated the inner surface once more with Silastic-xylene to reduce irregularities. Another animal died five days postoperatively of heart failure from outflow obstruction, due to almost 180° kinking of the bulb. No clotting was noted at autopsy. The other four animals are well up to 7-1/2 months after surgery. Since the ascending aorta is ligated distal to the anastomosis, all blood is forced to flow through the bulb. If it were to become occluded, the dog would die. Patency of the bulb and vessels was checked by periodic chest X-rays following injection of radiopaque dye into the heart (Figure 3).

One of the seven dogs with a polyurethane bulb died on the fourth day of clotting and partial kinking of the unit. We have the impression that occlusion in this case was due to incomplete evaporation of the polyurethane solvent, leaving an imperfect inner surface. The first dog in this series died six months after implantation. At autopsy, no clotting was found in the bulb, which had ruptured at a seam. This same occurrence with an early functioning unit led us to modify the sealing technique. One animal was accidentally sacrificed during X-ray studies to check patency four months after surgery. Too much anesthesia was given and dye was injected into the pericardial sac. There was no clotting. The other four dogs are well up to 6-1/2 months postoperatively.

A number of small pieces of the treated polyurethane have been attached to tissue at various sites in several dogs to determine the body's reaction. Histologic studies will be carried out on sacrifice of the dogs after about one year.

Biopsy and autopsy reports on dogs surviving 4 to 6 months showed relatively slight tissue reactions to either type of bulb on macroscopic examination. Histologically, a slight granulomatous chronic inflammation was observed in early cases and more acellular collagenous tissue in late cases. There was no significant foreign body reaction. The Dacron cuffs, which were invariably embedded in much thicker fibrous tissue than the Silastic or polyurethane bulbs, adhered firmly to the surrounding tissue. All anastomoses were patent and unconstricted. No early rupture was observed at the ligation of the aorta; the diameter of the lumen in this vessel was often 10-20% of normal. Microscopic findings included very slight necrosis of the aortic wall at the ligation, some fibrous transformation and, in one case, cartilaginous metaplasia. The lungs were well expanded and partially adherent to the unit and cuffs. In some instances small atelectatic areas were observed around the unit. Other organs revealed no abnormalities attributable to implantation of the auxiliary ventricle.

Hemodynamics. We have performed 20 system experiments with functioning U-shaped auxiliary ventricles. Flow was measured* in the aorta, the femoral, carotid and subclavian arteries and the circumflex branch of the left coronary artery. Pressures in the left ventricle, left atrium, aorta, femoral and carotid arteries were measured+ and recorded#.

We attempted to reduce left ventricular work by 40-50%. According to Sarnoff[6], myocardial oxygen consumption is very closely related to systolic pressure and systolic ejection time, i. e., to left ventricular work. Our own determinations were based largely on this relationship--calculated from the planimetric area under the systolic portion of the aortic pressure curve--which he refers to as the tension-time index.

Early in the development of the new unit, we found that the pumping chamber's displacement volume must be 80-100% of the stroke volume for good hemodynamic support. Prostheses were therefore designed and constructed for dogs in two weight ranges:

	18-22 Kg.	10-12 Kg.
Effective pumping volume	24-28 ml.	12-15 ml.
Residual volume	12-15 ml.	7-9 ml.
Diameter of Dacron cuffs	12 mm.	10 mm.

ECG (lead II), pressure changes in the femoral artery and left ventricle in a 20 Kg. dog (#2213) with the new unit are shown in Figure 4. In general, we applied air pressure about 50 mm. Hg higher

*Square-Wave Electromagnetic Flowmeter, Model 301, Carolina Medical Electronics, Inc., Winston-Salem, N.C.
+Statham Strain Gage, Model P23Db, Statham Instrument Co., Los Angeles, Calif.
#Sanborn 4-Channel Recorder, Model 954 A-100, Sanborn Co., Waltham, Mass.

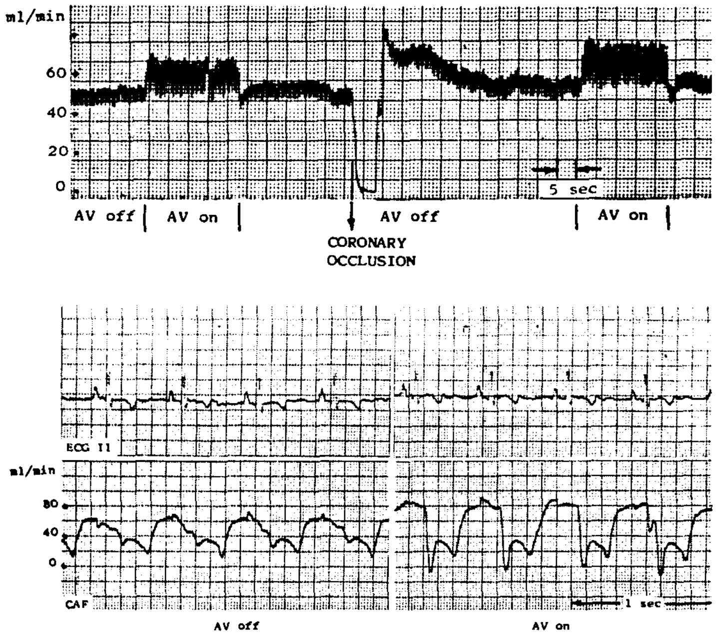

Figure 5. Mean blood flow (top) and pulsatile flow (bottom) in circumflex branch of left coronary artery with auxiliary ventricle (AV) "on" and "off".

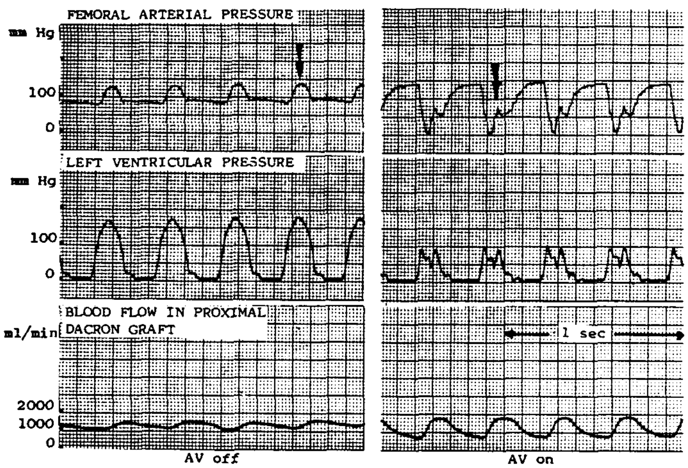

Figure 6. Reading from top: pressure changes in femoral artery and left ventricle, blood flow rate in proximal Dacron graft with AV "on" and "off" in same animal depicted in Figure 5. Arrows indicate cardiac systole.

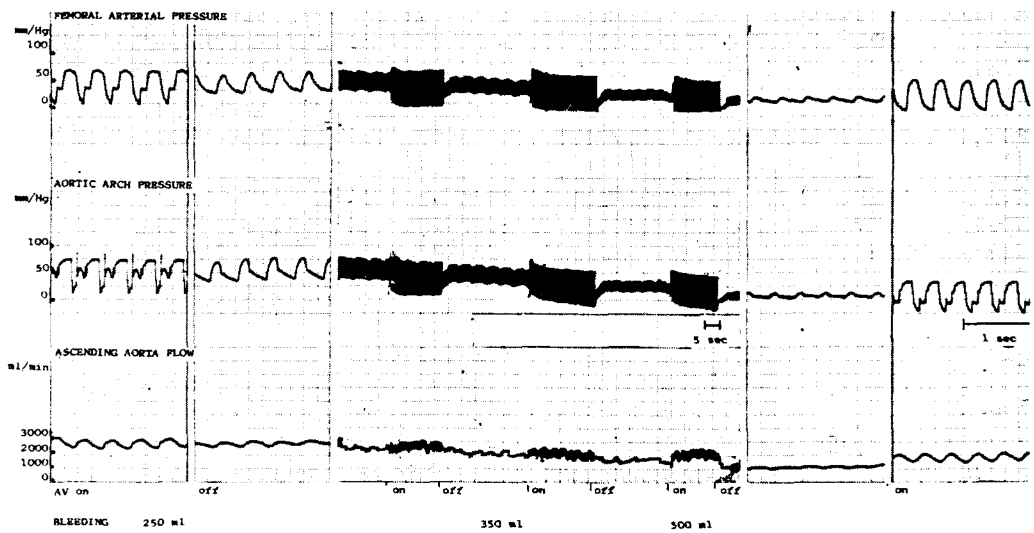

Figure 7. Hypovolemic pressure drop after withdrawal of 250-500 ml. blood from 20 Kg. dog. Femoral arterial pressure, aortic arch pressure, and ascending aorta flow shown with auxiliary ventricle (AV) "on" and "off."

than the peak systolic blood pressure in mm. Hg before pumping. This empirical parameter was later substantiated mathematically by calculating loss of power in the air valve, the tube itself and its orifice leading to the auxiliary ventricle. In Dog #2213, minus 10-30 mm. Hg pressure applied to the tube during systole reduced the tension-time index by 45%.

Under practically identical conditions, mean coronary flow in Dog #2375 was increased by 20%, and the pulsatile flow pattern showed a typical increase during diastole (Figure 5). During systole, particularly at the start when suction exerted by the unit at the aortic root lowered peak systolic pressure sharply, flow in the circumflex branch of the left coronary artery was slightly decreased. But coronary flow was augmented so significantly during diastole that the overall increase amounted to at least 20%.

The flow rate in the proximal Dacron cuff in this same animal was unchanged (Figure 6). In other cases, the aortic flow rate was somewhat increased; cardiac output remained the same or was 10-15% higher. Coronary flow is augmented and left ventricular work decreased only when cardiac output, i. e., peripheral perfusion, remains constant or is improved. This was the case in the peripheral vessels and carotid arteries of several dogs, as shown by pulsatile and mean flow measurements with the auxiliary ventricle operating.

With a hypovolemic drop in peripheral blood pressure after bleeding in a 20 Kg. dog (Figure 7), pressure in the femoral artery and aortic arch and flow in the ascending aorta were appreciably raised: after 400 ml. of blood was withdrawn, femoral arterial pressure rose from 25 to 50 mm. Hg; pressure in the aortic arch from 35 to 50 mm. Hg; and flow in the ascending aorta from 1600 to 2000 ml./ min. After 500 ml. of blood was withdrawn the corresponding increases were 15 to 45 mm. Hg, 15 to 30 mm. Hg, and 1000 to 1600 ml./min. To achieve the increased cardiac output shown in this figure, minus 25 mm. Hg pressure was applied to the air tube during cardiac systole. During this short period blood was actually sucked out of the physiologic ventricle, increasing the volume of circulating blood. The above-mentioned increase in diastolic pressure during pumping over the previous systolic pressure without pumping is very significant. The auxiliary ventricle can assist a weak heart by raising diastolic peak pressure over the preceding systolic peak and increasing cardiac output, thus improving perfusion of all peripheral and coronary vessels.

Seven dogs lived 16-28 days with U-shaped functioning units operating 5 to 10 hours daily. One animal (Dog #2263) lived 104 days with a Silastic unit operating a total of 303 hours. An infection which developed around the air tube persisted to the day of death despite local and systemic antibiotic therapy. This complication made it difficult to evaluate the anemia (hemoglobin 9.6, hematocrit 27, and red blood count 3,300,000) after three months of intermittent pumping. Plasma hemoglobin levels were usually between 25 and 45 mg.% and even after operation of the device never exceeded 85 mg.%. The anemia may have been to some extent due to the infection or to sublethal trauma to the red blood cells. X-rays on the 60th day clearly indicate the unit's position (Figure 8). On the 69th day, the dog bit off the electrodes at skin level, necessitating splicing. The last cut-down of a peripheral artery, on the 90th day, showed effective hemodynamic changes after 236 hours of pumping. The time delay was unaltered during this period. The dog's general condition remained good and it had gained one kilogram in weight when death occurred suddenly. An aneurysm about the size of a cherry at the point of ligation of the aorta-where the umbilical tape had cut through the ascending aorta--had ruptured into the left chest cavity. At autopsy, no clots or signs of previous emboli were evident. On macroscopic examination, the aneurysm was the only finding obviously related to the auxiliary ventricle.

There were no fatalities from embolism or occlusion in animals with a functioning unit. All deaths were due to infection from the air tube or to lung complications. The latter difficulties have affected many of our dogs undergoing thoracic procedures during the winter months.

SUMMARY

A newly developed, implantable, U-shaped auxiliary ventricle with no inside valves has been implanted in 33 dogs for patency and system experiments. The units are made of either Silastic 372 or a polyurethane-graphite mixture coated with graphite, benzalkonium, and heparin. Patency studies up to 7-1/2 months at the present writing strongly indicate the materials' durability and inertness to blood over prolonged periods. Acute and chronic hemodynamic studies (up to 104 days with 303 pumping hours) revealed a consistent 40 to 50% reduction in left ventricular work and a 20% increase in coronary flow with the cardiac output unchanged or slightly increased. Under conditions of hypovolemic

hypotension, peripheral blood pressure and cardiac output were significantly improved.

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Figure 8. X-rays of longest survivor (Dog #2263) on 60th day show position of unit.